On the ambiguity of 4D gravity monitoring of geological media

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The main concept of 4D gravity monitoring being realized on the short profiles is in common supplied by the analitical relations with the rapidly decreasing kernels. The monitoring perceptible depends on the non-tidal quasiperiodic variation of gravity field and also is influenced by the low-level geophysical fac-tors marked out by the Dvulit’s techniques.

1. On the background of monitoring.
Now on the amount, methods and opportunity to execute large-scale geophysical workings affect both the increasing accuracy and productivity of gravity sur-veying (this method at acceptable accuracy remains affordable prospecting and exploration solution due to improved equipment and GPS support) and a markedly sharp decline in volume measurements.

The first trend cause to review the methods of pro-cessing of the data acquired, in particular, a more accurate account of a Bouguer corrections [Bychkov, 2007]. The latter one, due to need of detection a de-eper sources of anomalies[1] , entails the revision of the

measurement method to account for subtle features of gravity anomalies without complicating the mathe-matical apparatus, measurement techniques and in-creasing the logistical costs. These features one can "hooks" wit the help of additional variable — the time.

In this regard, the world's "trends" of geophysi-cal observations gradually tend to the continuous 4D monitoring (Geophysics. — 2008. — **73**, № 6) of studied area, studying the evolution of the gravity field during exploitation time of the area or over du-ration of interval of his abrupt dynamic activation.

Nevertheless in the English-speaking sources the term "gravity variations" means temporal diffe-rence between the real anomalies in limited spa-ces, which sources are the objects with the rapidly changing of deep dynamics, while in the USSR’s literature this concept are reserved for a weak *qua-si-periodic fluctuations* in the super-long profiles crossing the area of contrasting modern vertical movements of Earth's crust.

[1] The possibilities of regularization methods in solving the problems of building complex cross sections at the present level of model representations on the geological environment are close to the technological limit.

But the idea of monitoring the some of its applications illustrate the work [Bolotnova, 2007]. Nevertheless, in these sources there are no mention on the background of monitoring — the gravity variations in the sense laid in the [Sobakar, 1972] and on their dependence on a series of *low-level* natural and man-made factors.

The use of *repeated* observations in a certain region in gravimetry branch is comparatively well known (its elements are used in the creation of regional density models of the Caucasus, in [Aleksidze, 1985], also [Yurkina, 1978]), although *continuous* in time to call them rather difficult, whereas in seismometry this for a long time there is a common practice. However, the organization of any high-precision measurements with the gravity as a separate parameter, its variational component should always be investigated to take into account.

2. On the variations of gravity. For the first time in the USSR's literature a various components of variation part of the gravity field are examined and a non-tidal *quasi-periodic variations* (QPV) of gravity (with amplitude within 3 to 5 times the measurement error) are picked out in [Sobakar, 1972]. For aim of their measurement was created a new triple basis. The methodological one means a use of the *heterogeneous Earth* model as in a physical-chemical as in a energy-efficient treatment. The methodological one relies on the fact that QPV have *maximum* at the intersection of tectonic structures of *different ages* and in the areas of *contrasted* modern vertical movements. The metrological one relies upon the observations on the network with *optimal density* and configuration by the multiple devices with a high coefficient of *reliability* and comparison of QPV gradients and the observed gravity anomalies.

The QPV itself obviously are closely related to endogenous processes of formation and development of density inhomogeneities of the Earth's crust and mantle, although not confined by them. The Earth's moment of inertia is changing during the redistribution of matter inside it, and as a consequence — the rotation regime and the corresponding gravity. Equilibrium Figure of the Earth is disturbed in the process of the redistribution, changing the gravity intensity. During isostatic restoration of the equilibrium patterns gravity changes once again. The range of processes mentioned generates the QPV gravity of the Earth. The reversible part of the process thus creates a periodic part of variation, and the irreversible part — a *non-periodic* part of the variations, which forms a stationary gravity anomalies.

There are correlation of large-scale mantle density inhomogeneities and tidal parameters of Earth, characterizing its tidal deformation. Earth tidal parameters (Love and Shida numbers) are based on the calculation of the relaxation amplitudes of gravity potential on the Earth surface and in its nucleus. Thereby a cross-correlation of QPV and the referred dynamic parameters of the Earth may be exist. This fact requires a separate studying.

Despite a low-intensity, anomalies of QPV gravity can be identified with confidence due to the peculiarities of the behavior of QPV curve time and the close inverse proportional correlation with the curves of vertical crustal movements. The latter one [Sobakar, 1972] is considered the result of commonness of processes in the upper mantle, affecting the QPV and the vertical movements. The total value of the QPV is treated as the sum of superpositions of variations of different origin, sign, period and amplitude. This total amplitude ultimately determines the evolution of Earth's gravity field caused by the evolution of the inhomogeneities of the crust and upper mantle.

3. The basis of monitoring. We call the *gravitational monitoring* a series of *periodically* repeated real-time *continuous* for a fixed period (Fig. 1) microgravity measurements and its processing subject to the influence of environment and area of application.

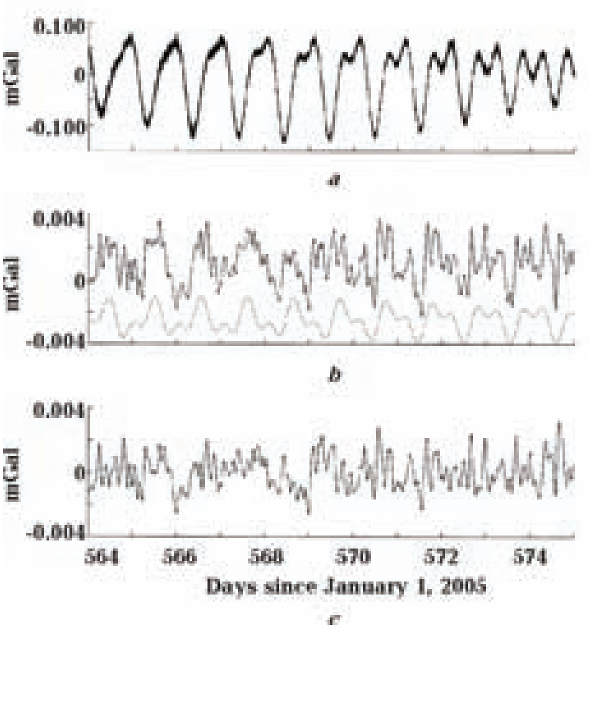


Fig. 1. 11-day series of measurements of gravity force: *a* — without filtering, *b* — with bandpass filtering, *c* — with correction for tidal effects.

The magnitude of the time interval depends on the quality of measurements, the measure of uncertainty of the observation data, the dynamics (amplitude and frequency) of the gravity.

Continuous connection of dynamics of the gravity and the environment parameters is the physical basis of gravity monitoring: thus to the undulations of the centimeter range are satisfied the gravity variations in a few mGal. If the deformation of surface relief of a certain area there is a direct consequence of the surface mass distribution, then gravity monitoring can be used to study a decompaction and fluid regime of the area studied.

The spatial distribution of variations of the vertical derivative values V_z of the gravity potential *directly correlates* with the area distribution of densities and temporal variations of V_z values clearly define the vertical variations of the fluid saturation.

Hardware base of the monitoring are a joint large-scale measurements of the terrain elevations by the GPS data and an absolute gravity values (hundreds of point on hundreds of km^2). The cheaper relative gravity measurement has serious limitations — the binding to the reference grid and the necessity for simultaneous accounting „zero creep". Nevertheless, in our case such measurements with proper methodical maintenance have the greatest prospect. A continuous measurements of gravity in boreholes may be used at some areas, as prevailing in the resolution that of the ground surveys due to the greater proximity to the disturbing sources and the elimination of surface effects. Some developments from the instrumental base of the marine gravimetry is advisable for use to compensate the influence of temperature and the other external factors.

4. On the extraction of a weak signal. In case studies of the 4D gravity monitoring (Geophysics, 2008. — **73**, № 6), the amplitudes of the signal are within the range of 20 mGal to 80 mGal. Within the boundaries of the active volcanoes of the signal amplitude increases to 300—600 mGal, and within watersheds ~200—250 mGal under a nonlinear accounting of "zero creep". Due to the repeatedness of measurements, fixing the residual gravity values at the observation point, we can estimate the accuracy of definition of the wanted signal in the time interval.

With the aim to extract a weak signal within the background noise in the gravimetry the methods of correlation analysis and calculation of some components of the gradients by the direct measurements of gravity are applied[2]. The signal wanted has distinguished by calculating the difference anomalies $\Delta g_d = \Delta g_m - \gamma h_z - \Delta g_{\text{def}} - \Delta g_w$, where Δ — the difference between 2 adjacent time samples, γ — a free air correction, h_z — a vertical displacement; Δg_{def} — a Bouguer anomaly of deformation[3]; $\Delta g_w = 2\pi G \rho_w \varphi \delta_z = 42 \varphi \delta_z$ — the impact of groundwater. Also the additional connection to independent observations at a reference point located near the investigated area is used.

A certain improving of the weak signal in the background noise can be received through statistical filtering effect of the temperature fluctuations using the algorithms with fuzzy logic [Andó, Carbone, 2004]. If there is lack of length of series observations, may be useful a low-order polynomial approximation with the appropriate "calibration" of the polynomial order. Besides, there is advisable the comparing of the filtering results with the data obtained from a nearby checkpoint from the area of observations.

As in the case of the QPV gravity measurements, there are (Geophysics, 2008. — **73**, № 6) noted the correlation of a weak signal with vertical shifts. Assuming the different frequency of gravity strength and noise variations it is used a frequency filtering to enhance the signal wanted. The analogy can be seen again in the marine gravimetry. In the plain terrain areas the signal has a small gradient, and this approach, in our opinion, is ineffective. In such case the impact of noise must be considered in other ways — by the *changing the geometry* of observation networks, with the help of the temporal filtering, the *derivatives calculation*, and so on, as mentioned in [Sobakar, 1972].

5. On the method of monitoring. To organize the monitoring in it's methodical way, perhaps, is best as in [Sobakar, 1972], and to study the metrology nuances on the geodynamic polygon with a set of geophysical measurements. Lack of infrastructure and equipment will significantly influence on the costs of monitoring at the landfill — its increases by the uncertain value. The using of a digital recording will avoid some difficulties in the early stages of surveying by simplifying the scheme of surveying and also it accelerates the creation of a digital model of the object. To overcome the financial and technological deadlock we see in the cooperation of different institutions with common usage of equip-

[2] Just as in the marine gravimetric surveying are applied the calculation of the vertical and horizontal gradients of gravity and their complex interpretation. This method of interpretation is tested on offshore oil-gas structures [Yurgin, 2006].

[3] Contribution from changes in volume due to compression of environment around the disturbing source, which implies the displacement of density boundaries in a heterogeneous environment.

ment, personnel, methods and the common overview of the research on the common object[4].

The application of the classical scheme of measurements on a *regular* network of points and the subsequent recalculation of the gravity values by the well-known Poisson integral is suitable for regional studies (Geophysics. — 2008. — 73, № 6), but in the local conditions, often used for gravity monitoring [Bolotnova, 2007], it has a number of shortcomings [Dubovenko, 2002]. Besides, sometimes for many reasons the organization of regular network is impossible, and the conversion from an irregular network on a regular basis is more complex task than the inversion of the geological media structure from data measured.

A solution of the inverse problems of gravimetry with data given on a pseudo regular network with using the environmental models such as "endless profile" leads to ill-conditioned systems of linear equations, generating meaningless results. Because of this, and to proceed from mostly short length of the actual measurement profiles, it is expedient an alternative approach.

To interpret the measurements on the short profiles is proposed [Dubovenko, 2002] the system of the linear integral equations with rapidly decreasing kernels:

$$S_{n+1}^{+}(x)=$$

$$= v(x)-\frac{1}{2\zeta_n(x)}\int_{-\infty}^{\infty} S_n^{+}(\xi)\left(\cosh\frac{\pi(\xi-x)}{2\zeta_n(x)}\right)^{-1} d\xi + S_n^{+}(x),$$

$$S_{n+1}^{-}(x)=$$

$$= v(x)-\frac{1}{2\zeta_n(x)}\int_{-\infty}^{\infty} S_n^{-}(\xi)\left(\tanh\frac{\pi(\xi-x)}{2\zeta_n(x)}\right)^{-1} d\xi + S_n^{-}(x),$$

$$\zeta_0(x)=S_0^{+}(x)+S_0^{-}(x)=v(x),$$

$$\zeta_0(x)=S_0^{+}(x)+S_0^{-}(x),\quad n=\overline{0,\infty}.$$

With the account of the above the method of [Bolotnova, 2007] is effective only in certain conditions (a regional background is a polynomial of 1-st degree; there are known the *densities* and *positions* of the boundaries of gravitating bodies on the surface, and these bodies are similar or have a common contacts). It implies in particular the construction of a spatial density model of the medium divided into 3 stages: the separation of gravity sources anomalies and the identification of *effective* depths of their occurrence and the *quasidensity* (zero approximation), then the detection of *true* depths and densities of disturbing bodies by the solution of the 2D inverse problem (1-st approximation) and the final solution in the ADG-3D package.

We propose in the method [Bolotnova, 2007] to use the software [Starostenko et al., 2004] and the program kit obtained in the PhD study [Dubovenko, 2002].

6. On the interpretation of data. The purpose of monitoring is to assess the depth of the source of anomalies and the changes of the volume according to the deformation data of the relief. It requires a knowledge on the surface mass distribution (from the gravity data). Deformations of the earth surface are received by the GPS data, having a series of advantages over traditional surveying methods[5]. Near-surface heterogeneities of the medium structure (as karsts, baird, areas of flooding and loosening), the complex structure of the area (folding, salt tectonics, faults), the factors of the absorption of wanted signal (the temperature, the instrumental effects) are limiting the efficiency of monitoring, without reducing its practical value.

In (Geophysics, 2008. — **73**, № 6) does not take into account the peculiarity of the gravity variations: a fluctuations in the value of its derivatives depend on the fluctuations of the low-level geophysical events (as anomalous atmospheric masses (Fig. 2),



Fig. 2. Western Ukraine gravity change as a result of movement of air masses [Dvulit, 1999].

[4] This way of the integrated monitoring (a collaborative gravity network) comes well many western companies.

[5] The independence from the time of day and the weather conditions, the automation, the continuity, the completeness, the reliable binding to the network.

the snow masses, the groundwater level, forest cover and changes in topography (Fig. 3) due to anthropogenic activities. We can take into account these effects through the entering corresponding corrections [Dvulit, 1999] into the solution of direct problems of gravimetry in the areas of study (it is assumed that due to long-term monitoring period of station is known the structure beneath the area).

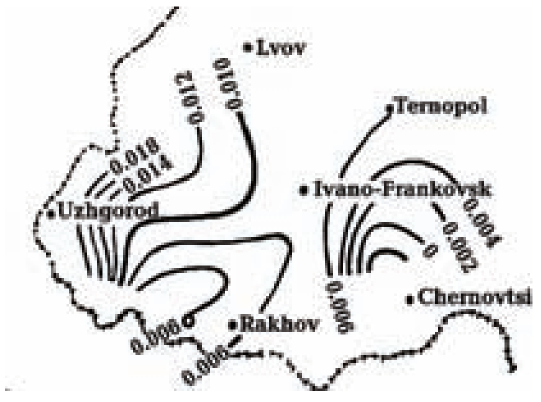


Fig. 3. Western Ukraine gravity changes as a result of mass transfer in the subsurface area [Dvulit, 1999].

The unjustified simplification of the analytical models of the geological media with the aim to reduce the ambiguity of interpretation in many cases may be the cause of incorrect results of calculations of the geometry sources and the vertical and lateral distribution of the density inhomogeneities. This especially takes place in cases where the external environment around the anomalous source is far from the assumptions of homogeneity. Reliable quantitative interpretation of the dynamics of the masses, for example, in the case of monitoring of hydrocarbons deposits can be produced providing the *well-known geometry* of the gravitating bodies (by the seismic data) and by the integrated interpretation of gravity field and deformation of relief data.

To avoid the ambiguity mentioned the the maximal accounting of the given *a priori* information about the media studied is needed. We propose to carry out it in 2 reciprocal supplementary ways:

1) by the constructing an appropriate model concepts (star-shape domains of known density inside the compact sets in the Banach space data);

2) by the adding into the discrepancy functionals in regularizing algorithms for some stabilizers of differential form, which eigenfunctions coincides with the eigenfunctions of the initial operators.

The section1 is justified in [Dubovenko, 2002], while section 2 — in [Chorna, 1999]. The solution of the specific inverse problems by the regularization is advisable by the algorithms of [Regularizing..., 1983] and similar one — on the basis of [Dubovenko, 2002; Starostenko et al., 2004].

7. Conclusions. The reasons considered above for gravity monitoring leads to next general issues.

The QPV of gravity should be taken into account in interpreting the results of 4D gravity in order to introduce appropriate corrections to the gravity surveys of different ages, to the long-term precision topographic mapping, to the clarifying the rheology of the investigated area, etc.

The weak signal must be extracted from noise by the *geometry control* of observation networks, by the temporal filtering or the *derivatives calculation*.

The measurements data interpretation on the short profiles give best results with the system of the linear integral equations with rapidly decreasing kernels being incorporated into existing 2D inversion.

The monitoring data must be corrected for the impact of fluctuations of the low-level geophysical events by the [Dvulit, 1999] technique.

An *a priori* information about the geological media may be accounted both by the selection of an appropriate media model and the special correction of regularization algorithms for ill-posed problems.

Repeated measurements of the gravity has a variety of applications but after the correction of the monitoring technique the results can be extended into the branch of QPV usage specified in [Sobakar, 1972]. The steps above seems to be necessary but maybe not sufficient to reduce the ambiguity of gravity monitoring interpretation. An experimental confirmation is expected.

From the gravity inversion of the monitoring data one can establish the *basic* image of density variations[6] not the absolute density values. There are great prospects for the interpretation of the temporal variations of gravity anomalies arising from changes of water-oil contact, or the level of reservoir water in the depths or any wells. It can be used as an inexpensive way of gravity monitoring of underground ecosystem of megapolises and the other geoecological solutions (the tracing the effects of floods, the landslides, the dynamics of pollution of underground basins, etc.).

[6] A decreasing of Δg stands for a decrease of hydrocarbons volume due to their production and thus, the lowering of gas-oil contact, but the increasing Δg stands for raising the level of the water layer of formation.

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